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THE APPLICATION OF A HIGHLY PERMEABLE MEDIUM TO REDUCE SPIN-UP TIME AND TO STABILIZE A LIQUID-FILLED SHELL

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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ABERDEEN PROVING GROUND, MARYLAND

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Laboratory experiments and projectile flight tests describe a technique that can reduce the spin-up time of a liquid contained within a cylinder. When the end wall regions of a cylinder are lined with a highly permeable material, the secondary circulation that controls the spin-up process is greatly enhanced, and a reduction in the spin-up time is achieved. Since the time to spin-up is decreased, then the time during which a liquid-induced instability could act is also decreased.

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I. INTRODUCTION

Bulk liquid payloads can disturb the flight of spin-stabilized projectiles.[1] Experience has shown that instabilities usually occur shortly after launch during the time when the liquid is being spun up by the projectile. A direct solution to such poor flight behavior would be to reduce the time required by the liquid to achieve rigid body rotation, thereby reducing the time of action of any destabilizing effects that could occur during the spin-up period. This report describes the use of a highly permeable material as an aid to liquid spin-up and projectile stability.

II. BACKGROUND

The response of a fluid to an impulsive change in the rotation of its container is a well studied problem and was reviewed by Benton and Clark[2]. This report will be restricted to the case of a homogeneous fluid in a cylinder, and a brief physical explanation of how the fluid and the container achieve an equilibrium state is included. Consider the case of the cylinder and the fluid at the same rotation rate, Ω_o, about the vertical axis of the cylinder. If the angular velocity of the cylinder is rapidly increased to Ω_1, the fluid in the interior of the cylinder is initially undisturbed. Near the end walls of the cylinder, however, the fluid experiences the increase of the angular velocity to the new value Ω_1 through viscous stresses. The increase in the velocity of the fluid produces an acceleration from the centrifugal force that is larger than the acceleration produced by the local pressure gradient, and as a consequence the fluid is thrown radially outwards. The fluid thrown out is replaced by fluid from the previously undisturbed core region of the cylinder, and a secondary circulation is established as shown in Figure 1.* Fluid that has been pumped outwards from the end walls returns to the core region, and its angular momentum is conserved as it moves towards the vertical axis of the cylinder. Hence, as the radial position (within the inviscid core) of a particle of fluid decreases it

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1. *Engineering Design Handbook: Liquid-Filled Projectile Design, AMCP 706-165, April 1969.*

2. *Benton, E.R. and Clark, A., Jr., "Spin-Up," Annual Review of Fluid Mechanics, Vol 16, pp. 257-280, 1974.*

**The circulation is sketched in only one quadrant of the cylinder, but occurs in all four.*

must spin more rapidly. This process continues until all of the fluid that was rotating at Ω_o passes through the viscous regions at the end walls of the cylinder, called Ekman layers, and finally achieves the rotation speed of the cylinder, Ω_1. This process that we have described is termed a <u>linear</u> spin-up process when the difference $\Omega_1 - \Omega_o$ is small, say ε. For the case where ε is not small, <u>nonlinear</u> effects are important. Primarily, these effects involve the neglection of convective derivatives in the core flow and viscous regions. For the case of the liquid initially not spinning (Ω_o=0) and Ω_1 large, the process by which fluid particles attain the rotational speed of the container is phenomenologically similar to that described above. The nonlinear case of spin-up from rest as applied to a liquid-filled projectile (Ω_o=0) was first solved by Wedemeyer[3], but substantial work has recently been accomplished by Sedney and Gerber.[4]

We wish to devise a technique for reducing the spin-up time of a liquid on board a projectile. For the case of <u>linear</u> spin-up, Kroll and Veronis considered a cylinder whose end walls were covered by a permeable medium, as shown in Figure 2.[5] Theory and experiments showed that a moderate reduction in the spin-up time could be achieved. We will investigate the case of spin-up from rest for a cylinder with permeable regions located at the end walls of a cylinder. A series of laboratory experiments have demonstrated that sizeable reductions in spin-up times are possible and that the azimuthal velocity of the core flow is not strongly dependent upon the vertical coordinate. Two projectile flights with associated liquid angular momentum histories demonstrate the practical application of the permeable medium concept.

III. EXPERIMENTS

The spin-up process with a smooth cylinder for either the linear or nonlinear cases is relatively slow due to the weak pumping action of the Ekman layers that are located on the cylinder end walls. The characteristic

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3. *E.H. Wedemeyer, "The Unsteady Flow Within a Spinning Cylinder," Ballistic Research Laboratories Report No. 1225, October 1963. AD 431846.*

4. *R. Sedney and N. Gerber, "Viscous Effects in the Wedemeyer Model of Spin-Up From Rest-Numerical Solutions," Bulletin of the American Physical Society, Series II, Volume 19, #10, pp. 1159, November 1974.*

5. *John Kroll and George Veronis, "The Spin-Up of a Homogeneous Fluid Bounded Below by a Permeable Medium," Journal of Fluid Mechanics, 40, part 2 (1970), pp. 225-239.*

time for spin-up for these cases can be stated in terms of the Ekman number, E, where

$$E = \nu/c^2\Omega \ . \tag{1}$$

The kinematic viscosity of the fluid is ν, the half height of the cylinder is c, and the steady rotation rate of the cylinder is Ω. The characteristic spin-up time for "Ekman spin-up" is $t\Omega = T_E$, where

$$T_E \propto E^{-1/2} \tag{2}$$

An impulsive spin generator, shown in Figure 3, was used to conduct experiments with cylinders whose end walls were lined with a permeable medium. The purpose of the experiments was two fold: (1) determination of the time to reach rigid body rotation of the fluid and (2) examination of the fluid dynamical processes by visual and photographic means. No measurements of torque or cylinder despin were made for these initial experiments. The half height and radius of the cylinder used in these experiments were c = 6.0325 cm and a = 3.49 cm. The depth of permeable medium located on each end wall was 1.27 cm. The spin of the container was 85 rad/s, while the container was 100% filled with tap water.* The particular type of permeable material used was an open pore industrial foam. Figure 4 shows large cylindrical sections of the types of foam that were used. These two samples have pore sizes of 60 and 10 pores per inch (PPI).

Several types of fluids were tested with dye tracers in an attempt to track the spin-up process. A very simple method, however, produced the best visual results. It was found that, if tap water was used, small air bubbles within the water and the foam provided excellent flow visualization. Bubble techniques are often used in steady flow problems, so care must be exercised in interpreting results from these unsteady experiments. During spin-up from rest of a bulk liquid (no permeable medium), a cylindrical front moves inwards from the vertical wall of the cylinder towards the center of the cylinder. This front separates essentially non-rotating fluid from fluid that is returning to the core after leaving the Ekman layers. Fluid in this annular region between the spin-up front and the vertical wall of the cylinder has appreciable rotational velocity, while fluid particles not within this annulus do not have a large rotational velocity. For the permeable medium case, let us examine the fate of a small bubble that has just left an end wall region after being thrown radially outwards by the permeable material. The bubble is carried by the circulation that returns the fluid particles to the core region. The centrifugal force on a bubble and on a particle of fluid with the same rotation rate is not identical. The density of the bubble is much less,

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**E = 3.10×10^{-6} *for these experiments.*

and hence the bubble will migrate towards the center of the cylinder. When the bubble reaches fluid that is non-rotating, however, it will not proceed to a smaller radial position since the non-rotating fluid experiences no centrifugal force. Hence, most of the bubbles will be trapped in the vicinity of the spin-up front as it moves radially inward. Although this description is simple, high speed motion pictures substantiate that such a process indeed occurs.

A typical sequence of still photographs enlarged fron 16mm films are shown in Figures 5-12. The slightly grainy appearance of the photographs is due to the enlargement process. Figure 5 shows the cylinder at rest. Numerals were attached to the cylinder to determine the number of revolutions. The light regions at the top and bottom of the cylinder are small cylindrical discs of foam (similar to the types shown in Figure 4). The top piece of foam is partly obscured by the end cap of the cylinder. Figure 6 shows air bubbles leaving the permeable medium, and we note that this phenomenon occurs in less than half a revolution. This may seem to be a very short time, but an Ekman layer is also formed in less than a revolution.[2] The fluid is pumped outwards by the permeable medium and then moves up the vertical wall. This is seen in Figure 7. Subsequently, the fronts moving towards the mid-plane of the cylinder are observed to meet in Figure 8. One may claim that the bubbles are leaving the permeable regions at all radial positions, since only a simple side view has been provided. Note, however, that the density of the bubbles is not uniform across the face of the cylinder. In the photograph, the center of the cylinder does not have as strong a concentration of bubbles as regions near the sides of the cylinder. Hence, we conclude that most of the bubbles are pumped out of the permeable media in regions that are close to the cylinder side wall, in a fashion similar to a classical Ekman layer. We postulate that these fronts are side wall viscous regions that must be established before the secondary circulation circuit is completed. After approximately three revolutions, the secondary circulation is established, and in Figure 9 the bubbles are seen to move towards the center of the cylinder. This process continues in Figures 10 and 11 as the bubbles form an inward moving, cylindrical front. After about one second, the bubbles are confined to a small columnar region along the vertical axis of the cylinder, as shown in Figure 12. At this time the bubbles and the numerals on the exterior of the cylinder were in synchronous motion as viewed in the motion pictures. Hence, the fluid is in rigid body rotation. During the spin-up process of the liquid, the cylinder spin rate was not steady.

Experiments were also made to determine the fluid motion for Ekman spin-up, i.e., with the foam removed, and the time required to reach rigid body rotation for similar conditions was 20-30 seconds. Two very important conclusions were realized from the permeable spin-up experiments. First, substantial reductions in the time required to reach rigid body rotation can be achieved. Second, the azimuthal velocity of the fluid within the core is essentially independent of the vertical coordinate.

IV. FLIGHT TESTS

Two projectiles were modified to incorporate sections of a 20 PPI foam similar to those shown in Figure 4. Figure 13 shows a standard M687 projectile. During the development of this projectile a spin-up instability of the liquid payload produced poor flights. A reduction in the payload compartment height eliminated the liquid instability and a wooden disc was inserted into the rear canister compartment. For the permeable media tests, special canisters were constructed that extended the inside height of the canister to a maximum.* These canisters were fitted with a cylindrical section of a 20 PPI foam on both the forward and rear end walls ($h/c = 0.24$) and were filled to 80% with water. The lengths of the standard, unstable, and extended canisters are 47.09cm, 52.65cm, and 53.42cm, respectively. The diameters are 10.78cm.

Flight tests were made at Wallops Island, Virginia, during May 1975. Fuze-configured yawsondes were used to monitor the inflight behavior of the test projectiles.[6] Yawsonde data are presented in terms of Sigma N and Phi Dot as functions of time. Sigma N is the complement of the angle between a vector drawn to the sun from the center of gravity of the projectile and a vector aligned with the spin axis of the projectile. Phi Dot is the derivative of the projectile's Eulerian roll angle with respect to the sun plane, i.e., the plane containing the missile's axis and the sun. For cases of large angular motion, oscillations are evident in the Phi Dot data, but the mean of these oscillations should be regarded as the spin of the projectile.[7]** Figure 14 shows an unstable flight history for a M687-type projectile (canister length is 52.65cm).

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6. *W.H. Mermagen and W.H. Clay, "The Design of a Second Generation Yawsonde," Ballistic Research Laboratories Memorandum Report No. 2368, April 1974, AD 780064.*

7. *C.H. Murphy, "Effect of Large High-Frequency Angular Motion of a Shell on the Analysis of Its Yawsonde Records," Ballistic Research Laboratories Memorandum Report No. 2581, February 1976. AD B0094210.*

**This longer canister closely resembled the unstable configuration of the M687 canister. Sufficient projectile hardware was not available to demonstrate that the extended canister would have produced unstable flights without the foam.*

***Spin data that have not been processed, by the methods of Reference 7 are labeled RAW PHI DOT.*

This instability was corrected by the insertion of the wooden disc, as previously discussed. Figure 15 shows a stable flight of one of the test projectiles, Round 7678, that were fitted with foam inserts. This flight history is quite typical for the M483A1 family of shell. The associated spin history is provided in Figure 16. On the second test projectile, Round 7679, only one of the optical sensors in the yawsonde worked properly; hence, only a spin history was obtained (Figure 17). Note that sizeable oscillations exist in the spin history of Round 7679 during the first 5 seconds of flight. These oscillations indicate a yawing motion larger than that of Round 7678 was present during this time frame, but that a stable motion, i.e., a smooth spin history, characterized the remainder of the flight.

With the knowledge of the aerodynamic properties of the projectile, the meteorological conditions, and the trajectory, it is possible to calculate on angular momentum history of the liquid from the yawsonde-determined spin.[8] A comparison between the angular momentum histories of Round 7679 and a control projectile is shown in Figure 18*. Let I be the angular momentum of the liquid at any time, while I_∞ is the angular momentum of the liquid if it were rotating as a rigid body at the muzzle spin rate. The angular momentum calculations in Figure 18 neglect any liquid spin-up effects that may have occurred in the tube. The peak value of I/I_∞ for the permeable case occurs at least 15 seconds earlier than the peak value for the control case.

V. DISCUSSION

A. Wedemeyer's Model

The analysis by Wedemeyer for Ekman spin-up of a completely filled cylinder uses an inertial coordinate system, where the r, θ, z-velocities are u, v, w. For rotational symmetry, the momentum equations for the core flow are reduced to

$$\frac{\partial v_o}{\partial t} + u_o \left(\frac{\partial v_o}{\partial r} + \frac{v_o}{r}\right) = \nu\left(\frac{\partial^2 v_o}{\partial r^2} + \frac{\partial v_o/r}{\partial r}\right) \tag{3}$$

and

8. *A. Mark, "Measurements of Angular Momentum Transfer in Liquid-Filled Projectiles," Technical Report ARBRL-TR-2029, November 1977.* (AD #A051056)

**The control projectile contained a single canister whose length was identical to that of the standard M687 canisters. The canister was filled with water to 90% of the available volume.*

$$\frac{1}{\rho}\frac{\partial p_o}{\partial r} = \frac{v_o^2}{r} . \tag{4}$$

The solution for v_o could be accomplished if a specific form of $u_o = f(v_o)$ were known with $v_o = 0$ at $r = 0$ and $r = a$ as boundary condition. In order to establish such an expression, Wedemeyer balanced the radial mass flow in the end wall regions to that of the core region. If the superscript tilde denotes a boundary layer velocity and if δ_E is the Ekman layer thickness, then

$$2\pi r\rho \, \{2 \int_o^{\delta_E} \tilde{u} \, dz + 2cu_o(r) \} = 0. \tag{5}$$

An approximate form for $u_o(r)$ for very early times was obtained from the similarity solution of a rotating disc in a fluid at rest, as solved by Cochran[9]. If the effects of the vertical wall of the cylinder are neglected, then this solution can be used to evaluate the radial mass flow in the Ekman layer as

$$\int_o^{\infty} \tilde{u} \, dz = 0.443(\nu/\Omega)^{\frac{1}{2}} \, r\Omega.$$

Hence, for early times,

$$cu_o = -.443(\nu/\Omega)^{\frac{1}{2}} \, r\Omega. \tag{6}$$

For very long times when a state of rigid body rotation exists, then $u_o = 0$. A very simple form for u_o that would be applicable for all times would be a linear interpolation based upon the early and long time solutions for u_o, or

$$u_o = k(v_o - r\Omega) , \tag{7}$$

where $k = 0.443E^{\frac{1}{2}}$.

The solution of (3) with the boundary and initial conditions can be simplified if the viscous terms on the RHS of (3) are dropped. The solution to the inviscid form of (3) was found by Wedemeyer to be

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9. *Cochran, W.G., Proceedings of the Cambridge Phil. Society 30, p. 265, 1934.*

$$v^* = \frac{r^* e^{2k\Omega t} - \frac{1}{r^*}}{e^{2k\Omega t} - 1} \quad \text{for } r^* \geqslant e^{-k\Omega t} \tag{8a}$$

and

$$v^* = 0 \qquad \text{for } r^* \leqslant e^{-k\Omega t} , \tag{8b}$$

where $v^* = v_o/a\Omega$, $r^* = r/a$, and $t^* = t\Omega$.

The angular momentum of the fluid provides a simple measure of the characteristic Wedemeyer spin-up time. Let I be the angular momentum of the fluid at any instant in time and I_∞ be the angular momentum of the fluid when it is in a state of rigid body rotation, then

$$I/I_\infty = 1 - \exp(-t/T_W) , \tag{9a}$$

where

$$T_W = (2k\Omega)^{-1} = 1.13\Omega^{-1}E^{-\frac{1}{2}}. \tag{9b}$$

Equation (9b) particularizes the Ekman spin-up time, T_E, stated in (2) to the Wedemeyer solution.

B. Permeable Medium Spin-Up

The model developed by Wedemeyer for Ekman spin-up considers a core region (where the dependence of the azimuthal velocity on the vertical coordinate is small) and viscous regions that establish a secondary flow. The simple experiments conducted with the spin-generator indicate that the azimuthal velocity in the core region is also independent of the vertical coordinate for the case of permeable medium spin-up and that the permeable regions close to the end walls induce a secondary circulation. Hence, as a first approximation to the permeable medium spin-up problem, the core flow could be described by (3) and (4) with a new $u_o = f(v_o)$ relation based upon the flow in the permeable medium end wall regions. Even so, such an approximation would require careful analysis.

A review of the results of Kroll and Veronis provides some interesting points of discussion. The flow within the permeable regions was described by Darcy's Law. In simple terms such a description merely requires the pressure gradient to be proportional to the velocity. No time-dependent effects were considered and isotropic flow properties were assumed. The core flow was considered along with an Ekman layer that separated the core and permeable regions. Also, without justification, the radial pressure gradients within the Ekman layer and the permeable region were matched. Although these concepts were successfully used for a linear spin-up analysis, it is felt that the case of nonlinear spin-up would require a more elaborate treatment and these assumptions and simplifications would not be adequate.

The characteristic spin-up time as derived by Kroll and Veronis is defined as T (linear spin-up for a permeable medium) $\equiv T_{\ell p}$, where

$$T_{\ell p} = \frac{1}{\Omega} \left[\frac{1 + 4N^2}{(4Nh/L) + 2N E^{\frac{1}{2}} + E^{\frac{1}{2}}}\right] , \qquad (10)$$

where $N = k\Omega/\nu$, k is the permeability, ν is the kinematic viscosity, E is the Ekman number, h is the depth of the permeable medium, and L is the half depth of the fluid. L corresponds to c-h in Figure 2.

In nonlinear spin-up with a permeable medium, if a significant reduction in the time to spin-up is to be achieved, then $N \gg E^{\frac{1}{2}}$ and (10) becomes

$$T_{\ell p} = \frac{1}{\Omega} \left\{\frac{1 + 4N^2}{4N(h/L)}\right\} \qquad (11)$$

An examination of (11) or the application of (11) for projectiles is not possible since only a small amount of spin stand data is available. Also, an accurate method for the determination of permeability must be established.

VI. CONCLUSIONS

It has been demonstrated via laboratory test and flight tests that a highly permeable medium can significantly reduce the spin-up time of a bulk-filled liquid payload. Analytical studies should be made to establish a correlation between laboratory and flight data, and a reliable method for the identification of the permeability of candidate media should be established. An example of a simple adaptation of the permeable medium concept is shown in Figure 19. A preliminary compatibility investigation between white phosphorous (WP) and some industrial foams has been completed, but extended tests should be conducted for other military payloads. This application of a highly permeable medium and a recent WP/felt wedge concept are similar in philosophy, and analytical models for flow through permeable media would be applicable to both.[10]

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10. *W.P. D'Amico and W.H. Clay, "Flight Tests for Prototype Felt Wedge/ White Phosphorous Improved Smoke Concept," Ballistic Research Laboratory Memorandum Report ARBRL-MR-02824, April 1978.* (AD #A054643)

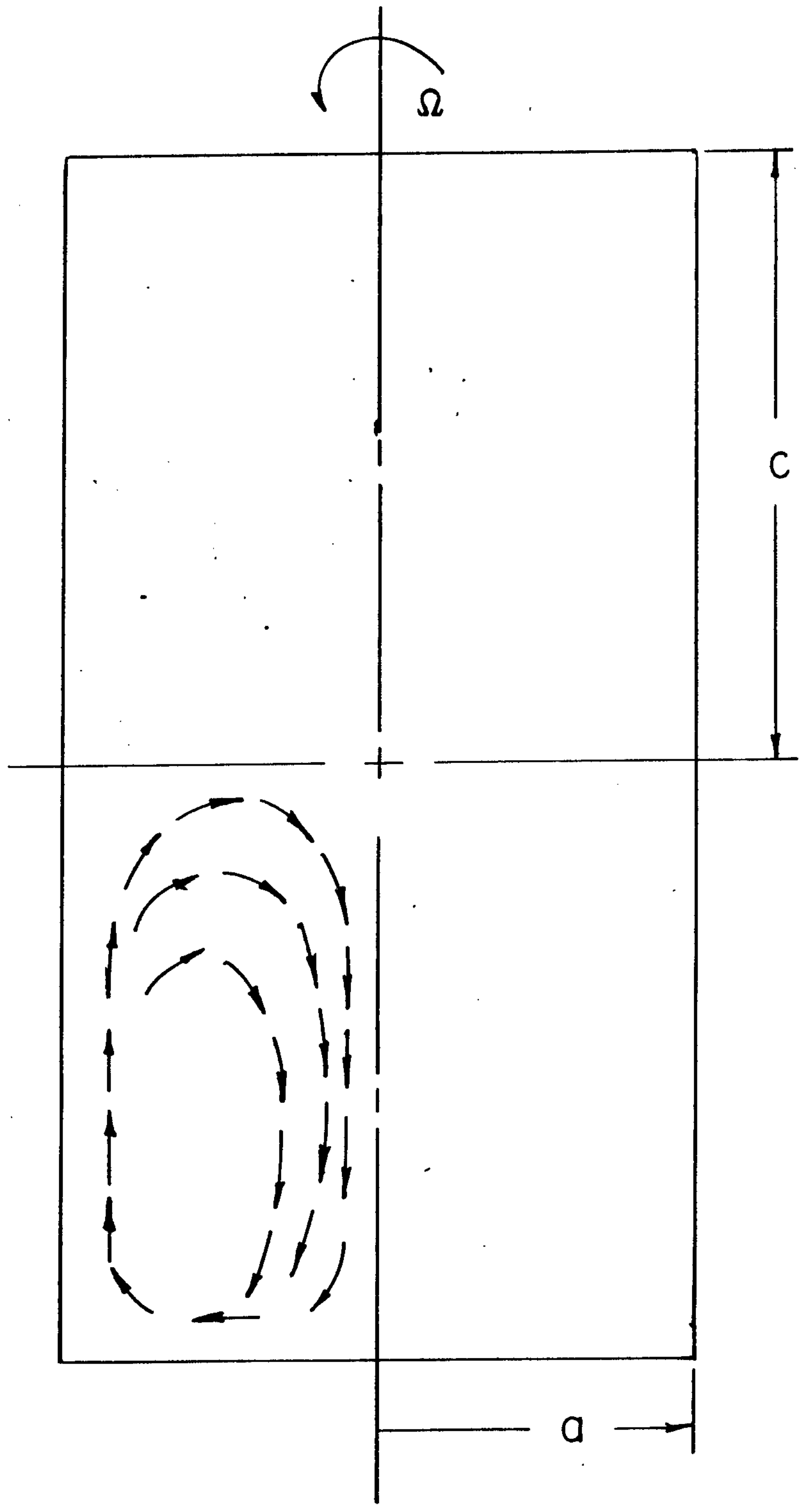

Figure 1. Secondary Flow for Ekman Spin-Up in a Cylinder

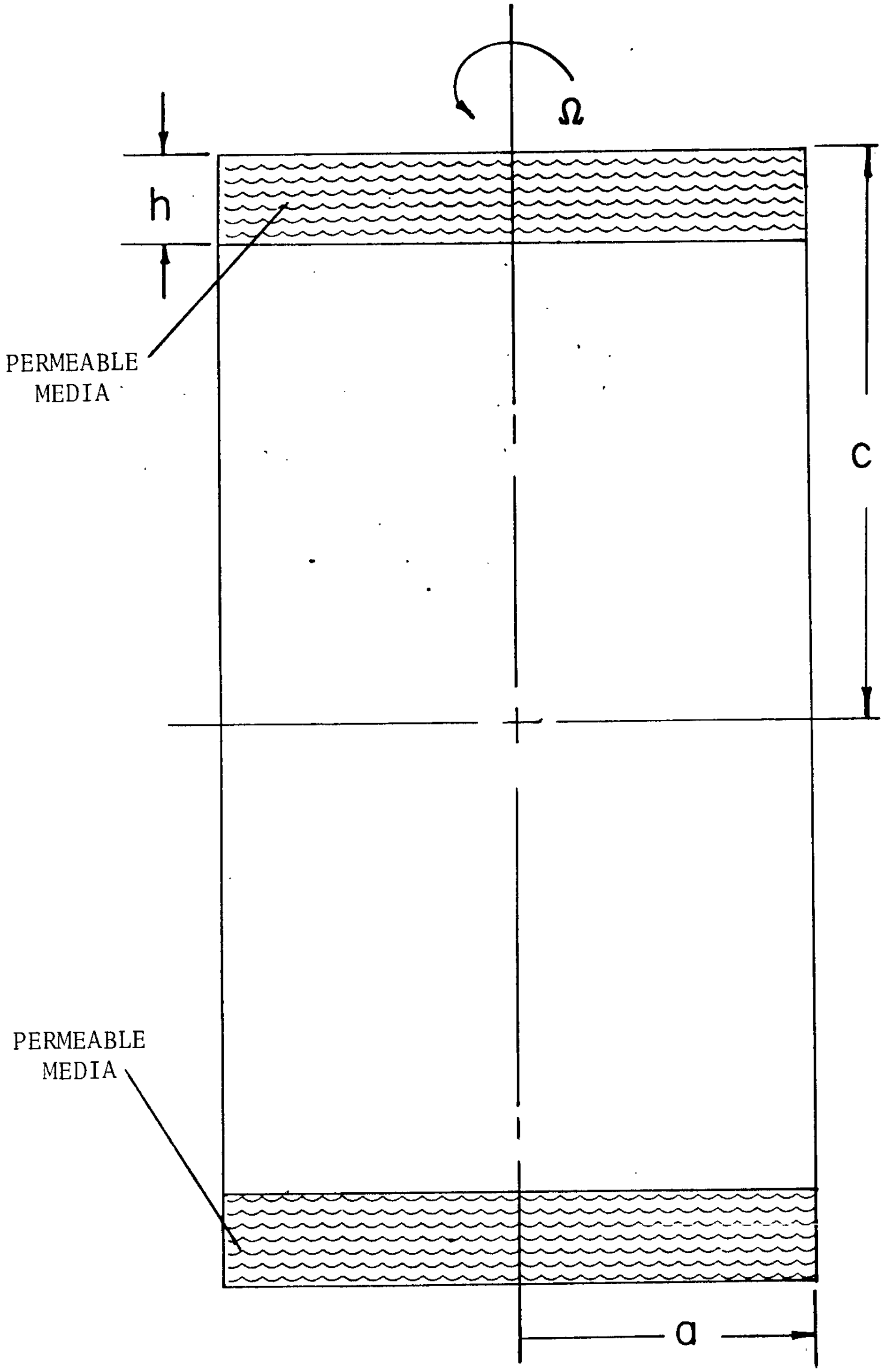

Figure 2. Permeable Medium Located on the Cylinder End Walls

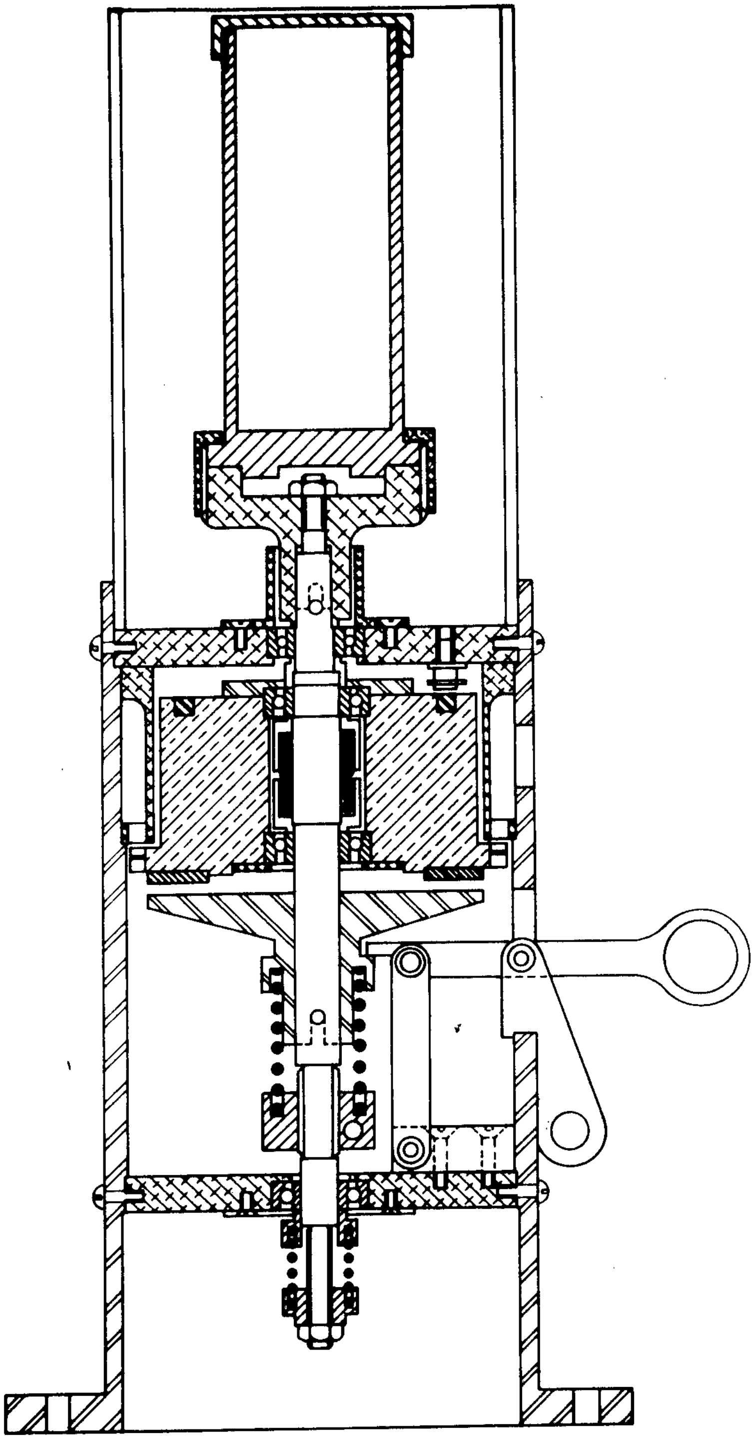

Figure 3. Impulsive Spin Generator

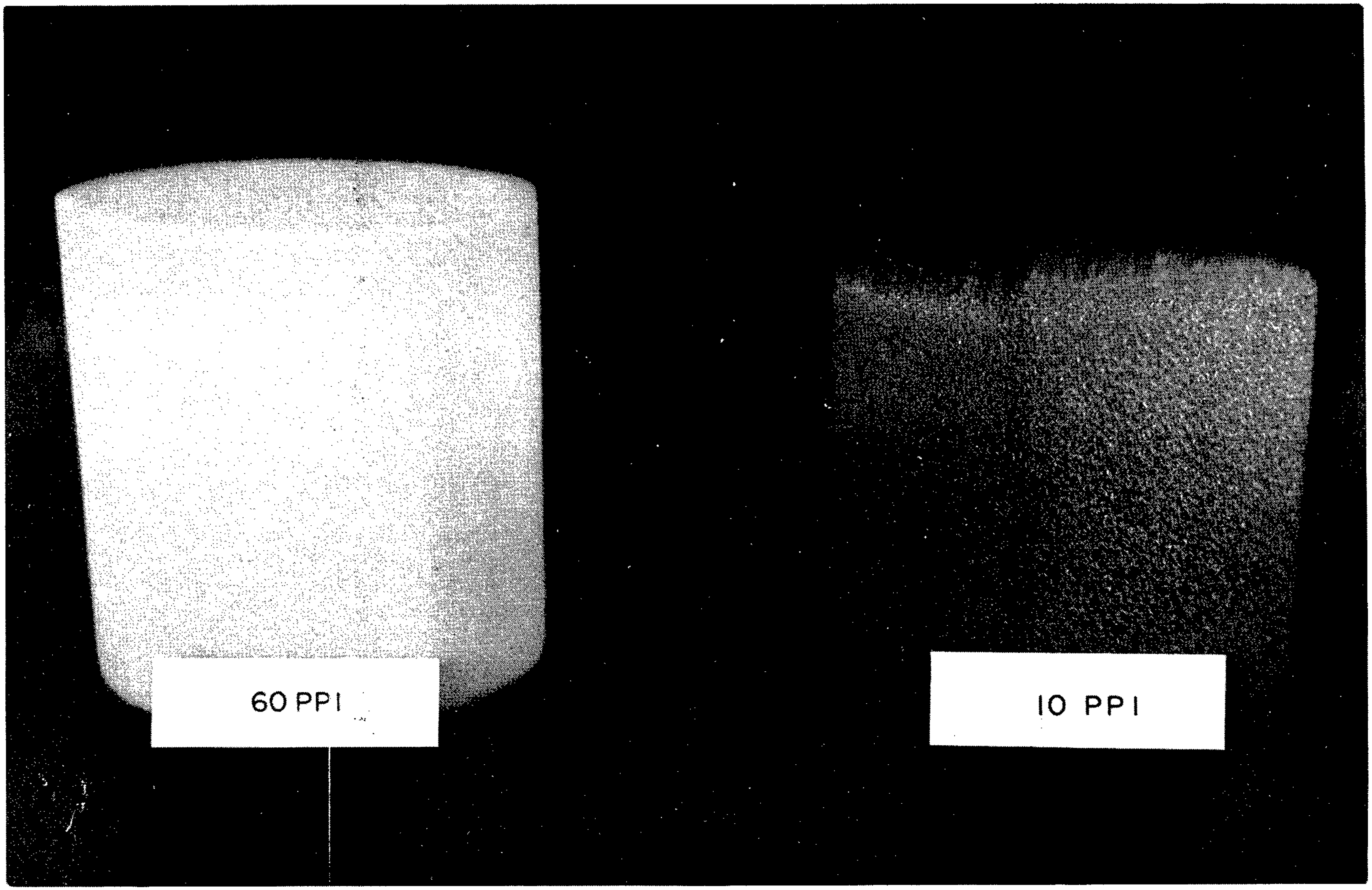

Figure 4. Samples of 60 and 10 Pores Per Inch (PPI) Foams

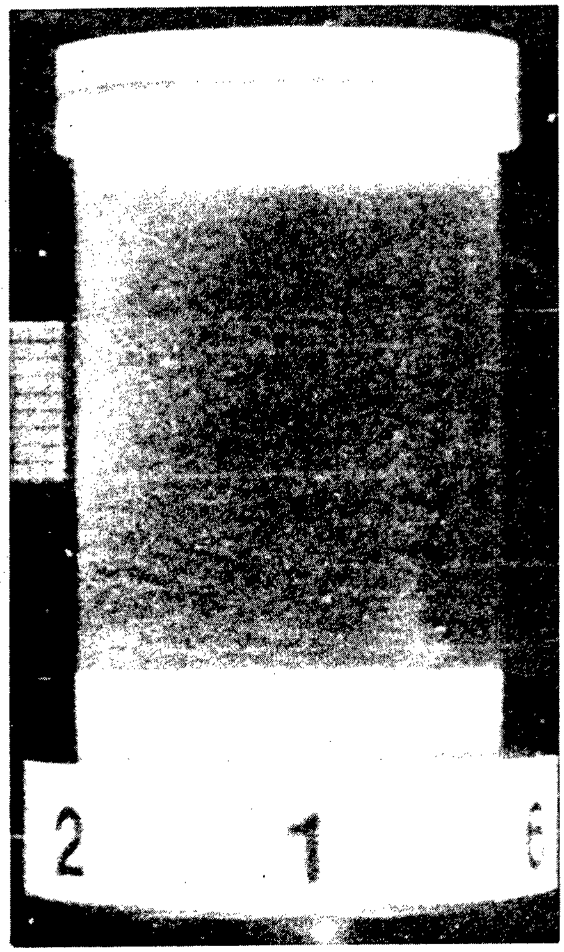

Figure 5. Impulsive Spin Generator: Zero Seconds and Zero Revolutions

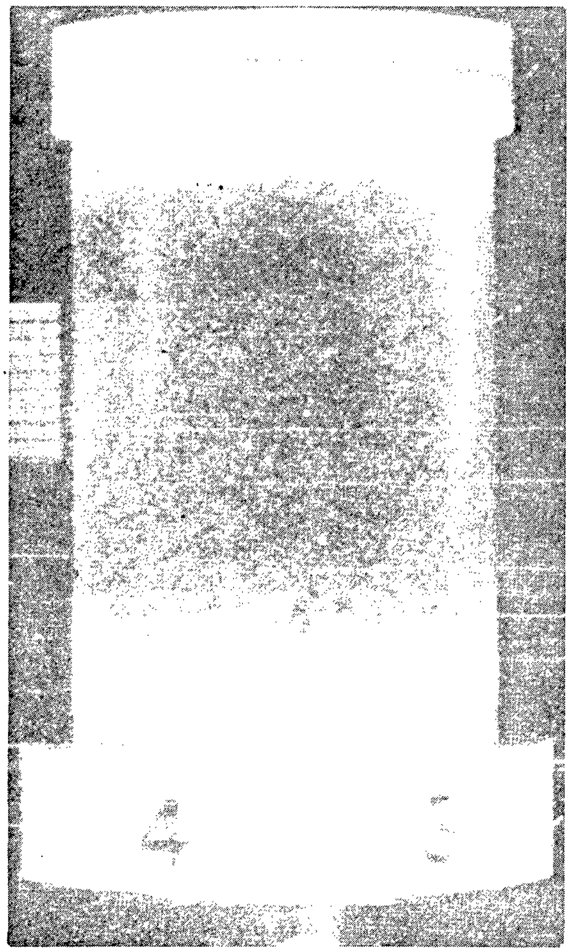

Figure 6. Impulsive Spin Generator: 0.058s and 0.42 Revolutions

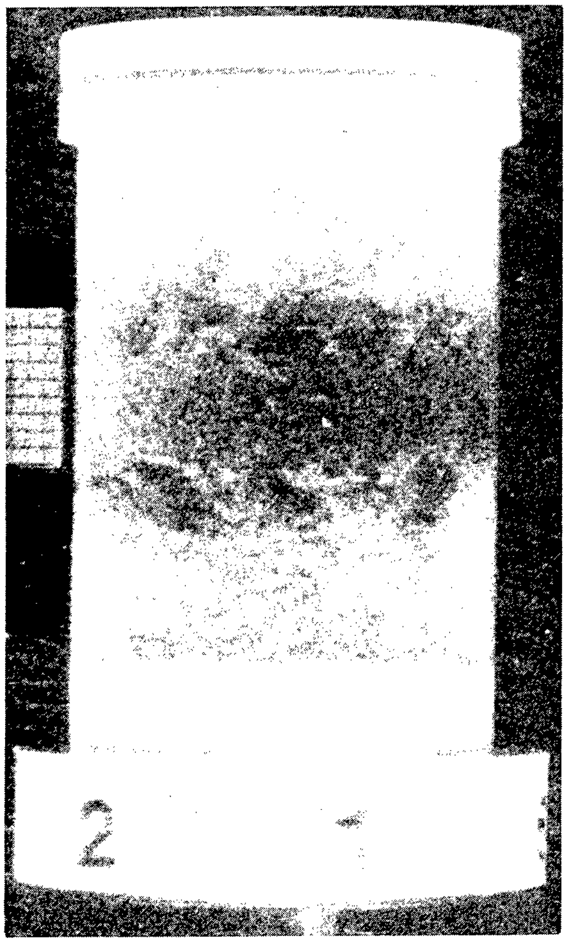

Figure 7. Impulsive Spin Generator: 0.10s and 1.0 Revolutions

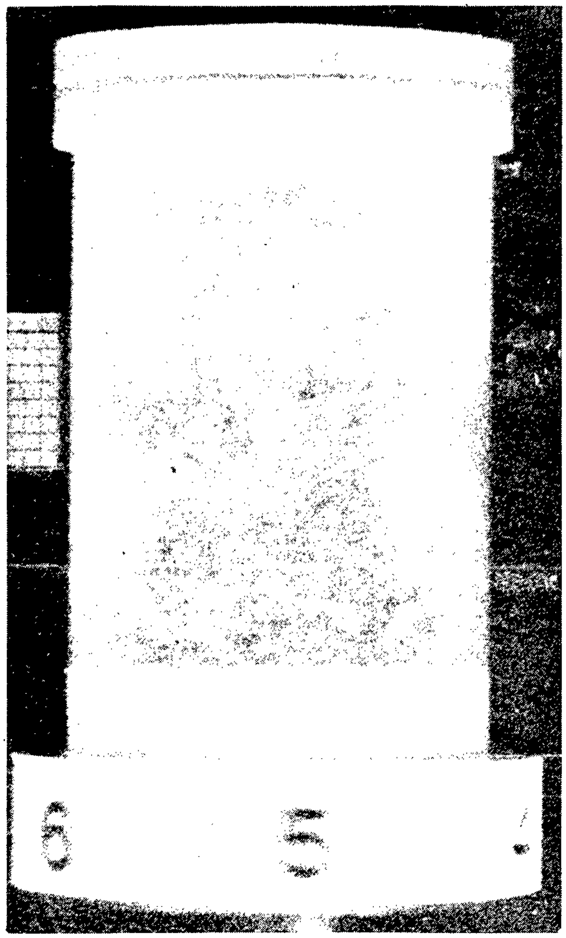

Figure 8. Impulsive Spin Generator: 0.142s and 1.67 Revolutions

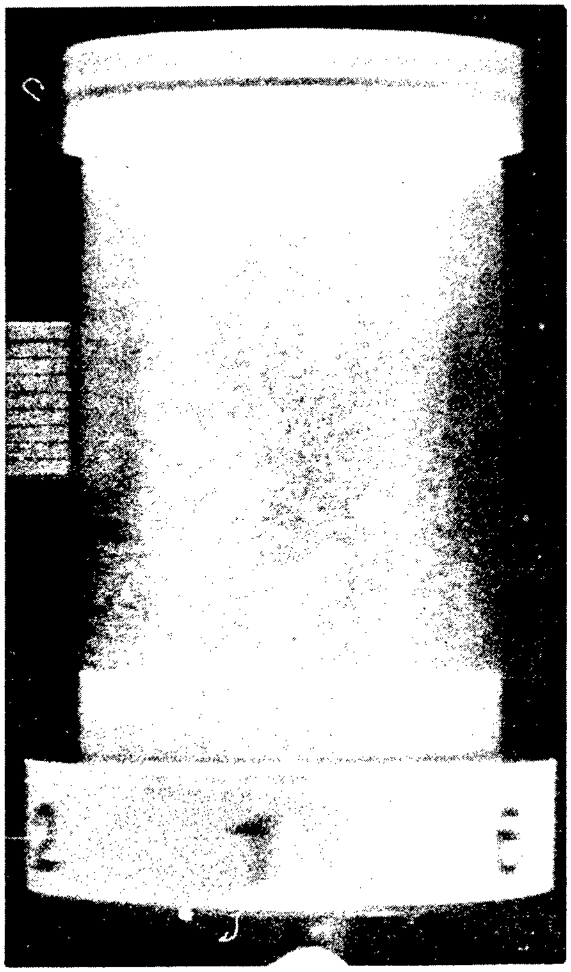

Figure 9. Impulsive Spin Generator: 0.23s and 3.0 Revolutions

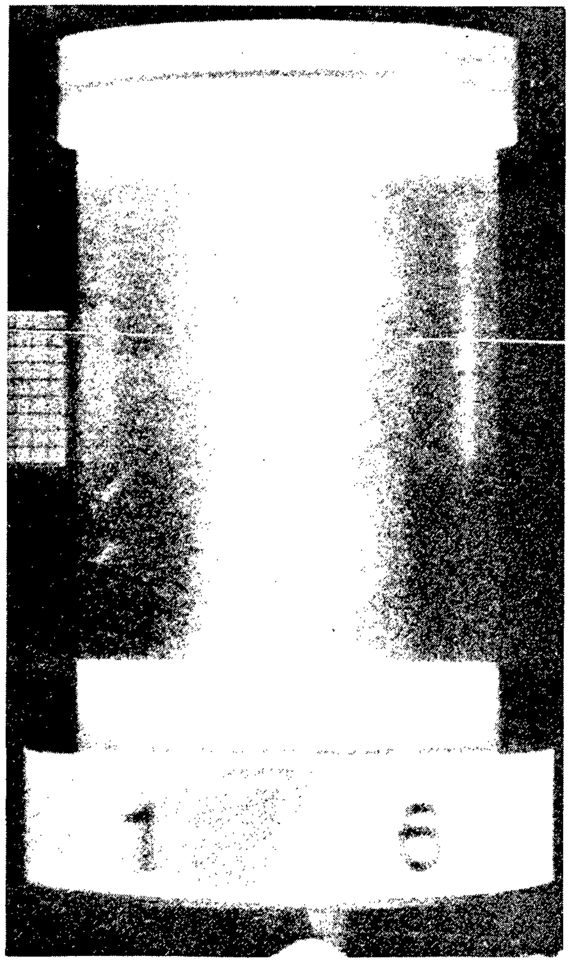

Figure 10. Impulsive Spin Generator: 0.367s and 4.92 Revolutions

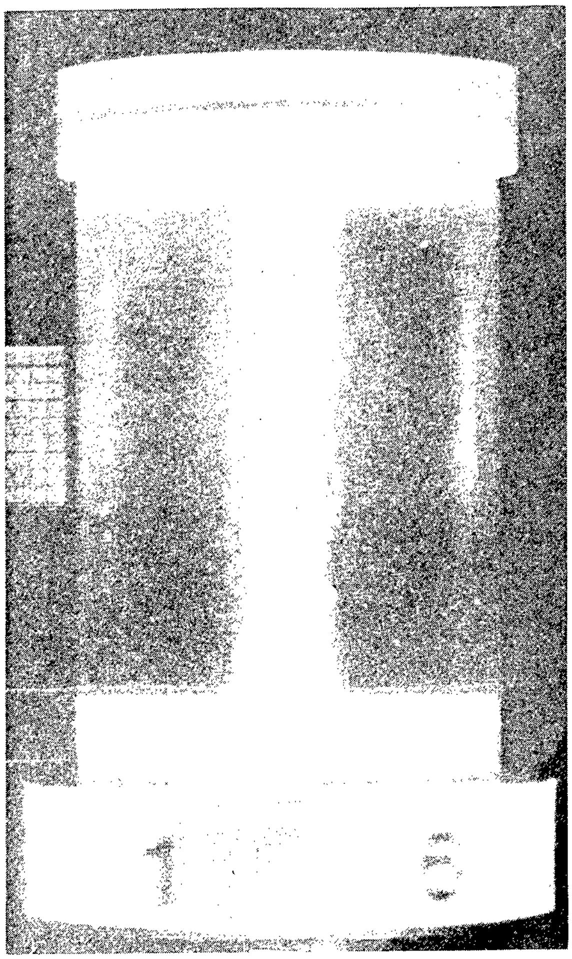

Figure 11. Impulsive Spin Generator: 0.588s and 7.92 Revolutions

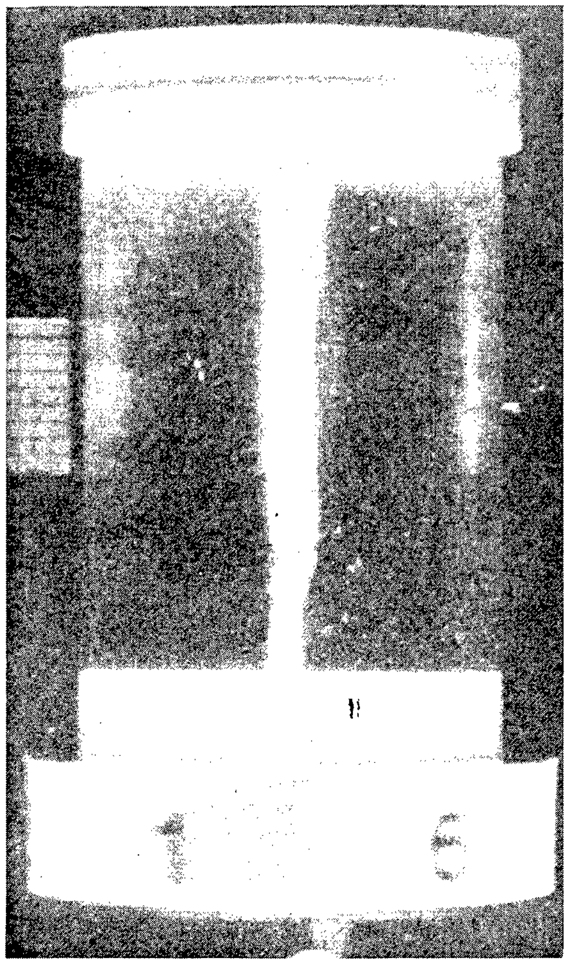

Figure 12. Impulsive Spin Generator: 0.975s and 12.92 Revolutions

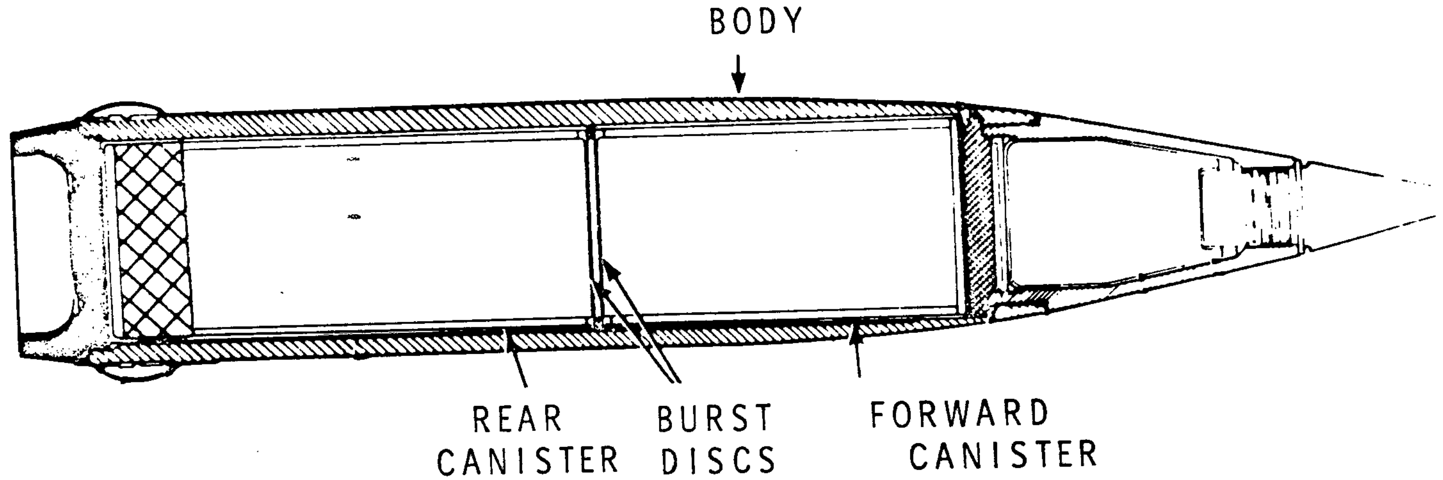

Figure 13. Standard 155mm, M687 Binary Projectile

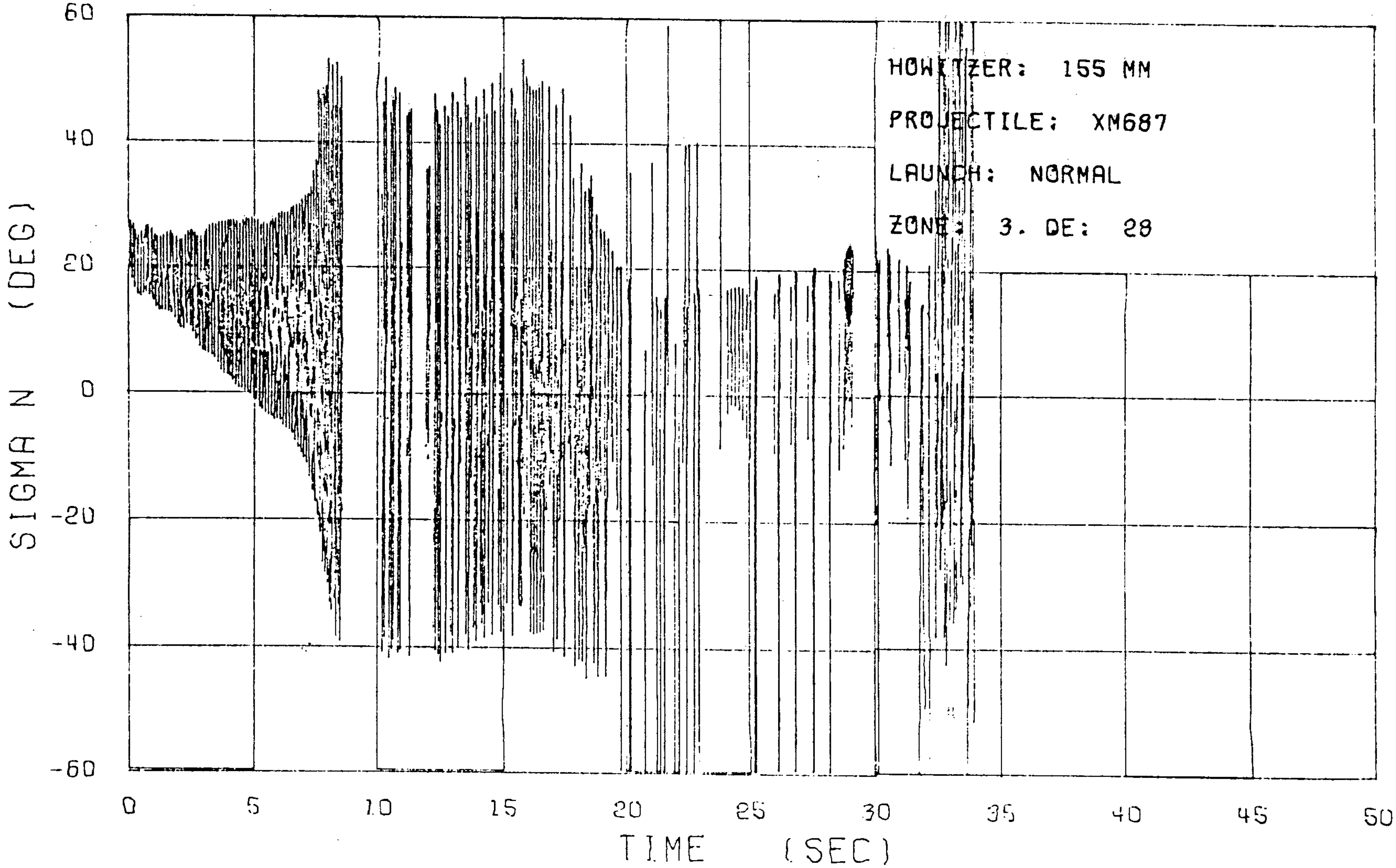

FIGURE 14. SIGMA N VS TIME ROUND E1-5974

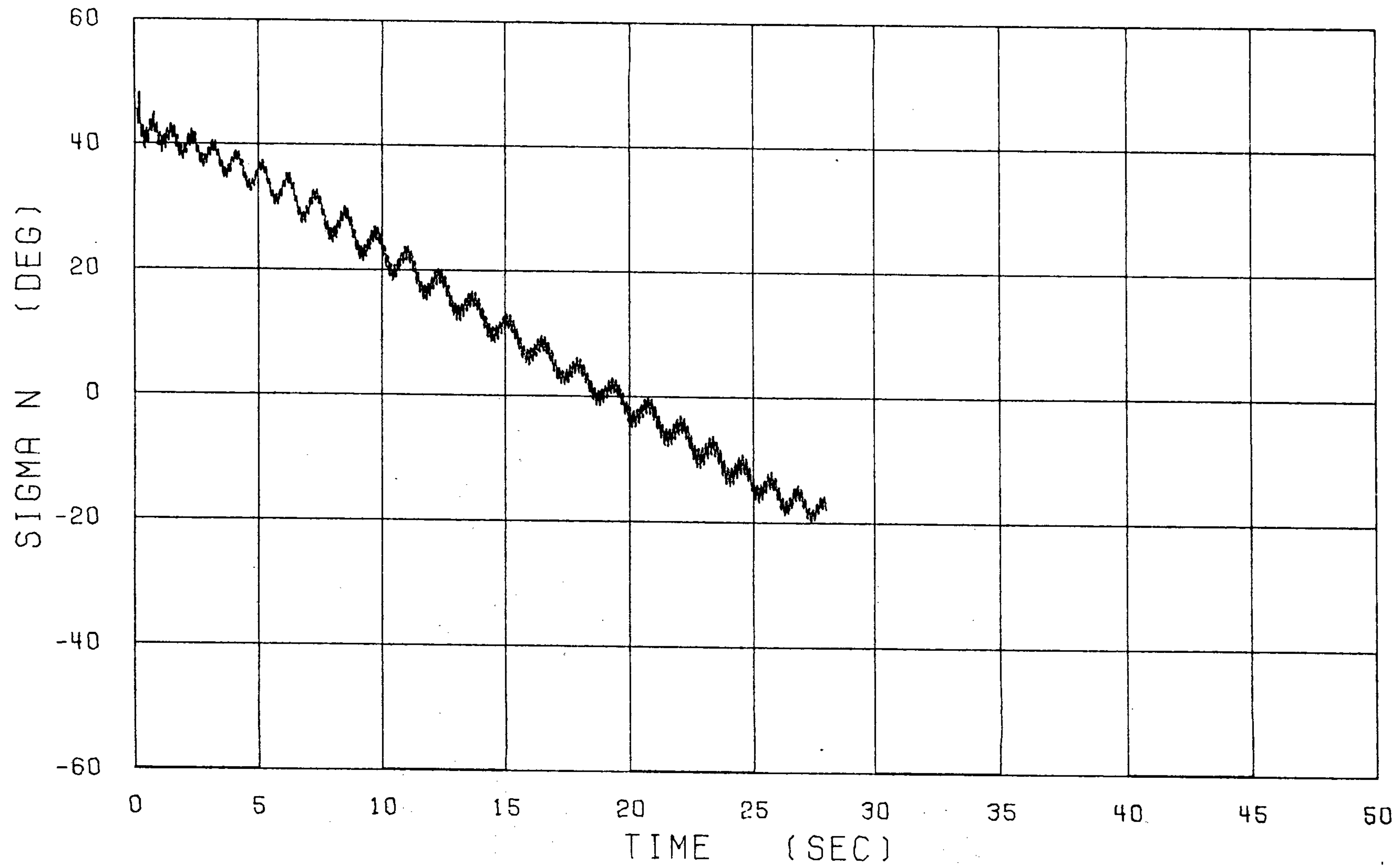

FIGURE 15. SIGMA N VS TIME ROUND 7678

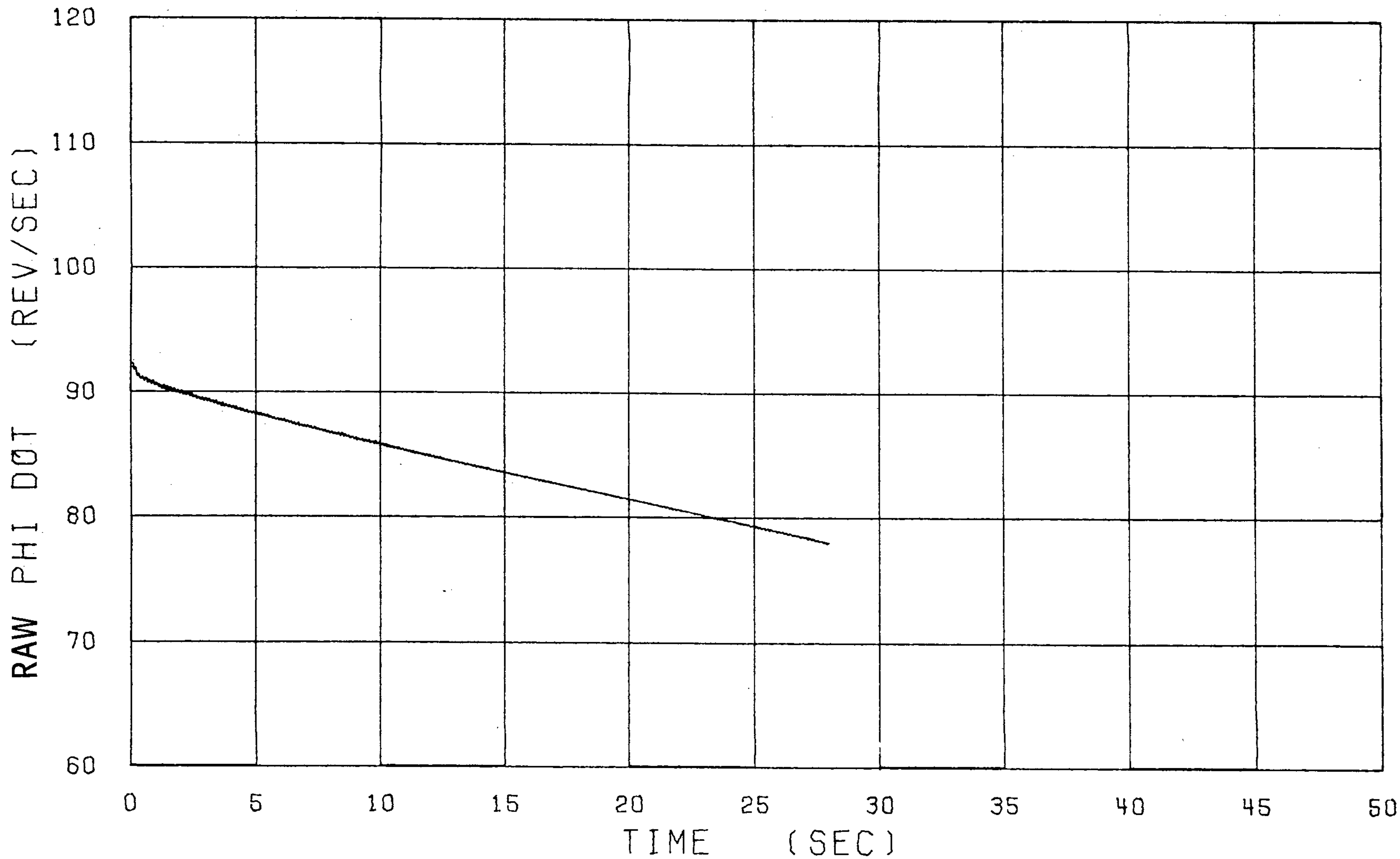

FIGURE 16. PHI DØT VS TIME ROUND 7678

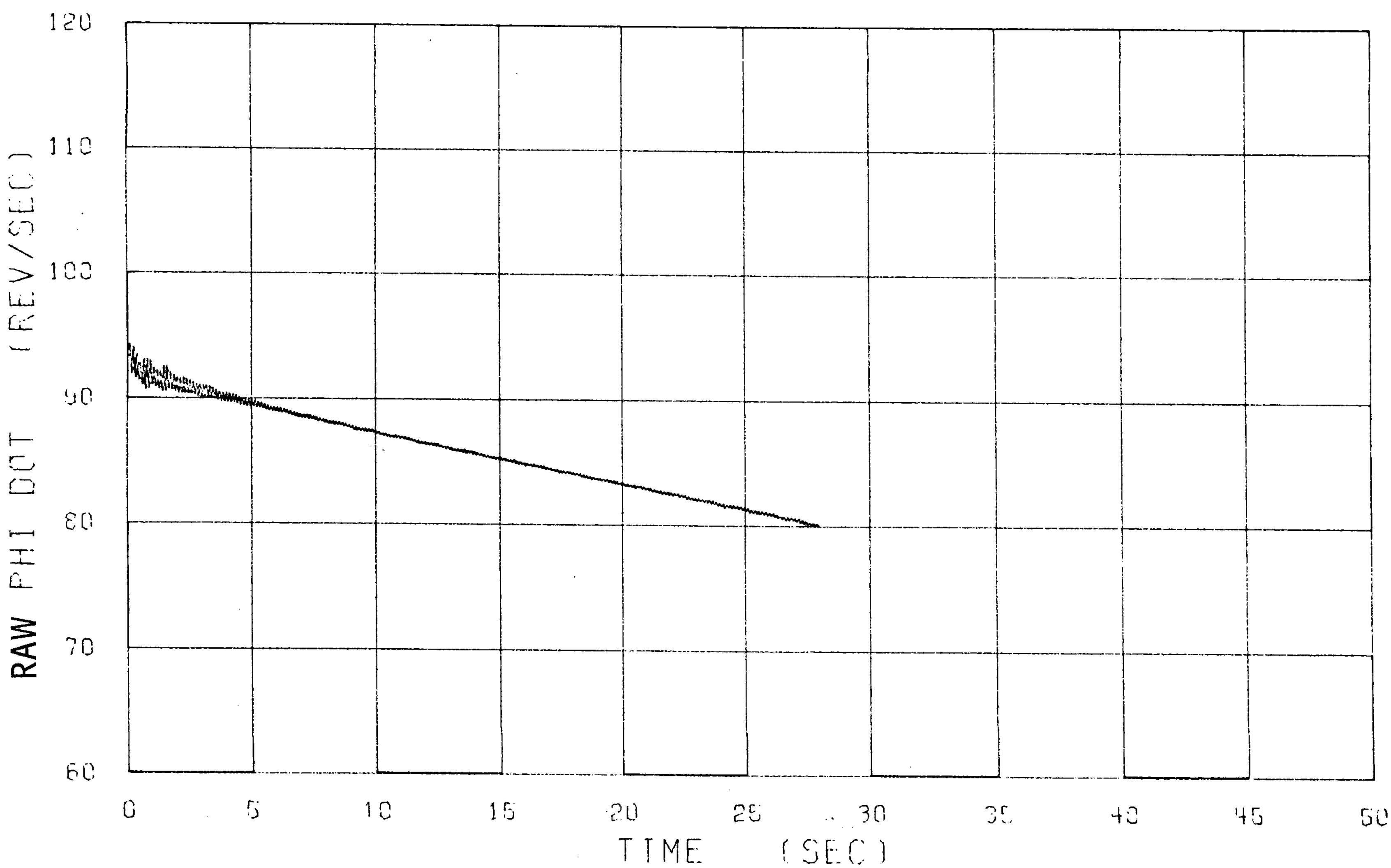

FIGURE 17. PHI DOT VS TIME ROUND 7679

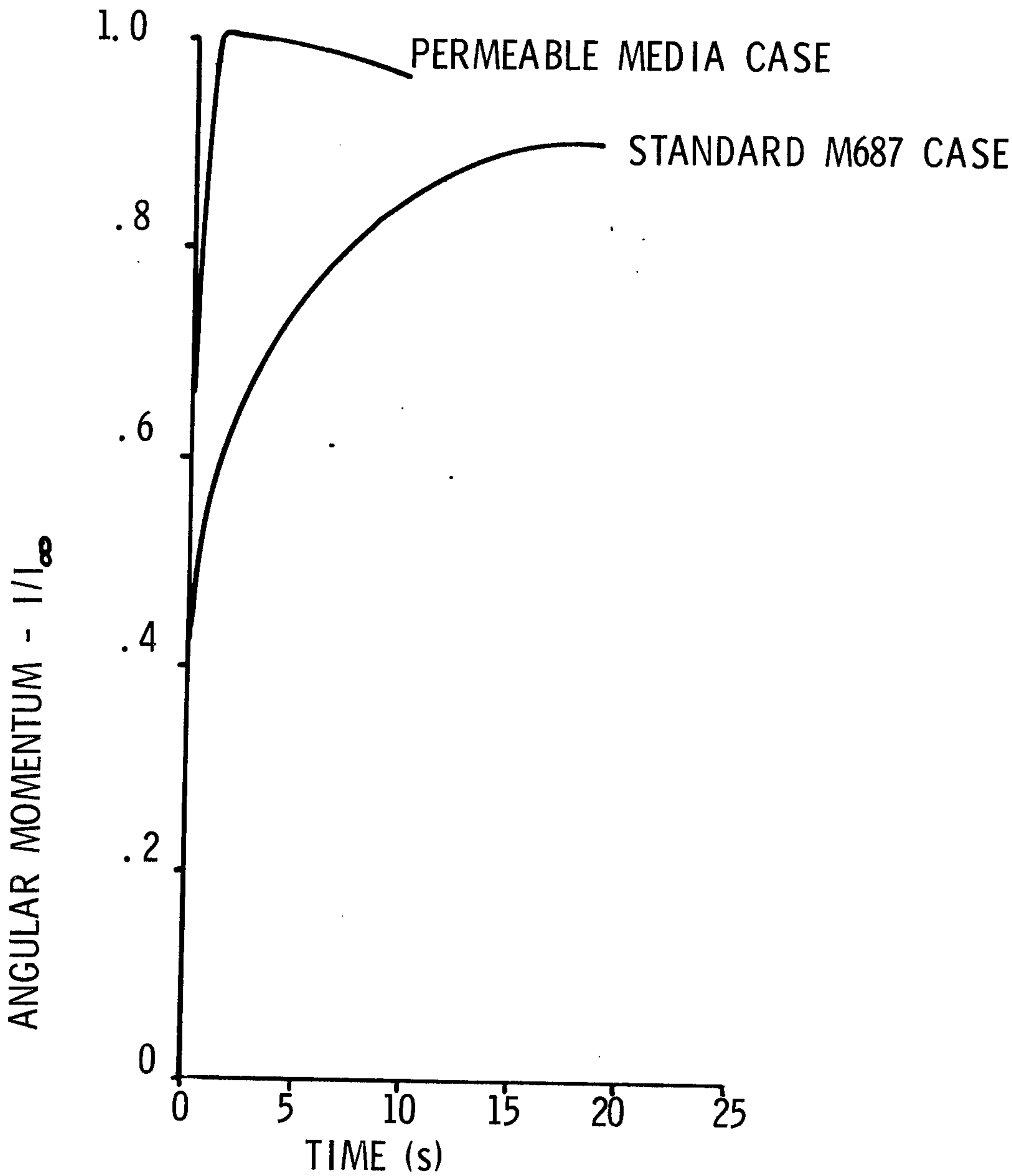

Figure 18. Comparison of angular momentum histories of liquid payloads for the permeable media and standard cases.

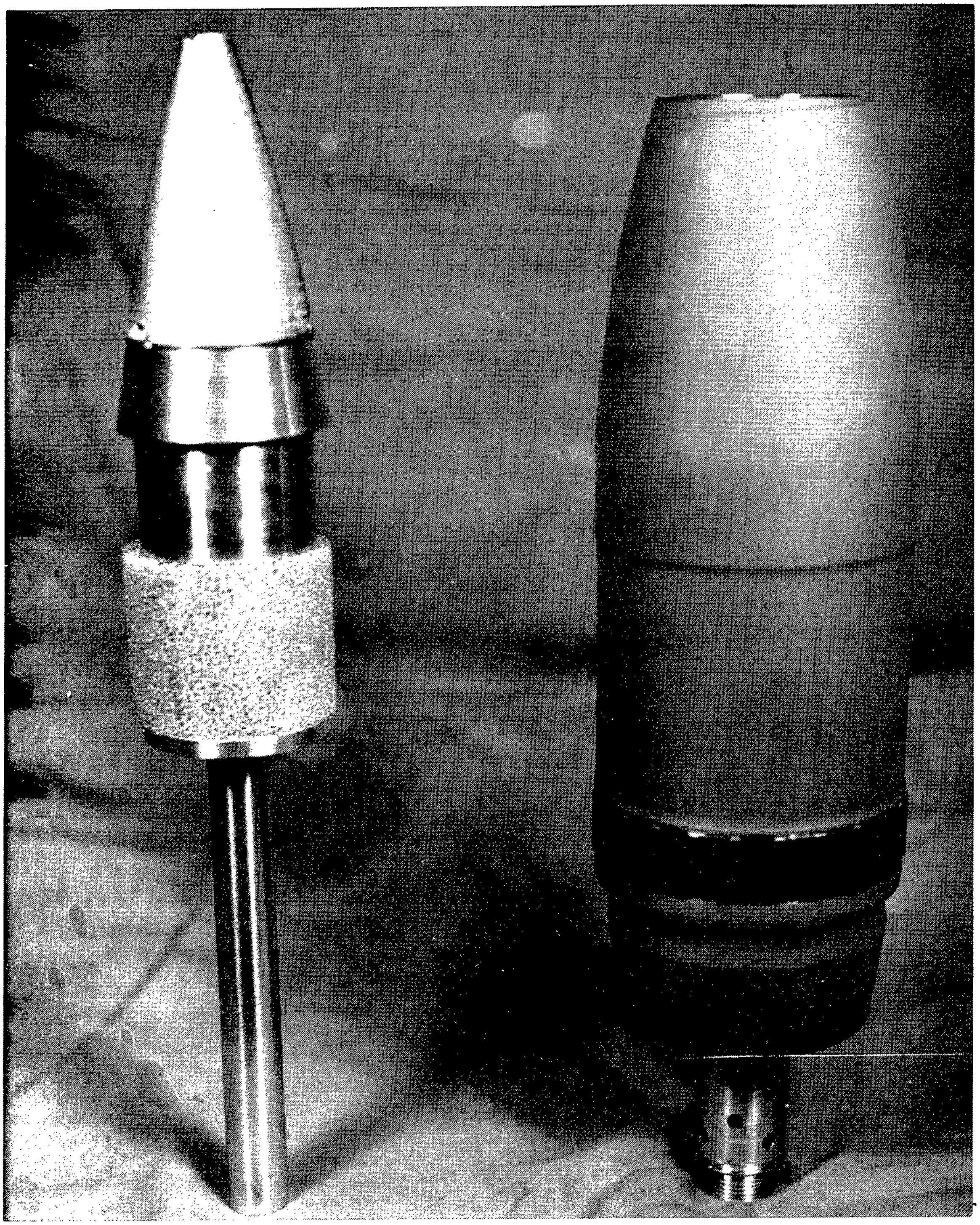

Figure 19. Application of the Permeable Media Concept to a 4.2-Inch Mortar

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